PATENT APPLICATION ENTITLED

"FEATURE MODELING IN A FINITE ELEMENT MODEL"

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<u>Date Filed</u>:

June 29, 2001

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FEATURE MODELING IN A FINITE ELEMENT MODEL

Related Applications

[0001]   This application claims priority under 35 U.S.C.
§ 119(e) to United States Patent Application
No. 60/215,697 entitled "Method and System for Oil
Reservoir Simulation and Modeling" by Stephen R.
Kennon, Kok Thye Lim, Scott A. Canaan, Steven B.
Ward, Stuart W. Pond, Jr. and Edward J. Barragy,
filed June 29, 2000, which is incorporated by
reference as if set forth in its entirety herein.

TECHNICAL FIELD OF THE INVENTION

[0002]   This invention relates generally to methods for
modeling physical systems using finite element
analysis and, more specifically, to methods for
modeling features of the physical systems, such as
fractures in a geological structure, for which one or
more properties change at the boundaries between
these features and the surrounding regions of the
physical system.

BACKGROUND OF THE INVENTION

[0003]   Physical systems can be modeled mathematically to
simulate their behavior under certain conditions.
There are a wide variety of means to model these
systems, ranging from the very simplistic to the
extremely complicated. One of the more complicated
means to model physical systems is through the use of
finite element analysis. As the name implies, finite

element analysis involves the representation of individual, finite elements of the physical system in a mathematical model and the solution of this model in the presence of a predetermined set of boundary conditions.

[0004]   In finite element modeling, the region that is to be analyzed is broken up into sub-regions called elements. This process of dividing the region into sub-regions may be referred to as discretization or mesh generation. The region is represented by functions defined over each element. This generates a number of local functions that are much simpler than those which would be required to represent the entire region. The next step is to analyze the response for each element. This is accomplished by building a matrix that defines the properties of the various elements within the region and a vector that defines the forces acting on each element in the structure. Once all the element matrices and vectors have been created, they are combined into a structure matrix equation. This equation relates nodal responses for the entire structure to nodal forces. After applying boundary conditions, the structure matrix equation can be solved to obtain unknown nodal responses. Intra-element responses can be interpolated from nodal values using the functions which were defined over each element.

[0005]   Finite element models are often used to determine the behavior of geological structures such as oil reservoirs under certain conditions. Finite element

models can simulate the flow of oil through
particular regions of the reservoir in response to
the various oil recovery operations, such as
drilling. The resulting information is useful in the
analysis of the reservoir and the management of the
oil recovery operations.

[0006]   Conventional finite element models, however, have
certain limitations which prevent them from
accurately simulating the behavior of the physical
systems which the model. For example, in the case of
the oil reservoir, the finite element model may
represent a particular property of the reservoir
using a mathematical function which gradually changes
according to the position within the reservoir. It
may be very difficult to force these functions to
approximate changes in the properties which occur
very abruptly as a result of geological features
within the reservoir. For instance, a reservoir may
have two distinct layers, each of which has a
substantially different value for a given property
(e.g., porosity.) at the boundary between these two
layers, a mathematical function representing the
value of the property might therefore have to make an
immediate transition from one value to the other at
the boundary between the layers. Even if the
mathematical function can be adapted to represent the
respective values for the property at the boundary
between the two layers, such a function would
typically be very complex and would require a great
deal of computational resources.

[0007]   It would therefore be desirable to provide a
method for more accurately representing the values of
certain properties within a finite element model,
particularly across the boundaries of features within
the model for which the properties change rapidly or
are discontinuous, while at the same time requiring a
relatively small amount of computational resources.

SUMMARY OF THE INVENTION

[0008]   One or more of the problems outlined above may be
solved by the various embodiments of the present
invention. Broadly speaking, the invention comprises
a method for simulating a physical system using a
finite element model which comprises at least two
distinct models corresponding to distinct regions
within the modeled system.

[0009]   In one embodiment of the invention, a method
comprises defining a finite element model
corresponding to an oil reservoir. A second finite
element model corresponding to a feature found within
the reservoir is also defined. The boundaries of the
feature model are used to carve out a portion of the
reservoir model. The feature model is then inserted
into the carved out portion of the reservoir model.
Although they represent portions of the same oil
reservoir, the properties corresponding to the two
finite element models can be defined independently.
In some cases, there will be nodes which are common
to both models and must therefore take on different
values for certain properties, depending upon whether

the values are used in the solution of the reservoir model or the feature model. An evaluator is therefore associated with each of the models. The evaluator determines whether the value of a property is governed by the definition of the reservoir model or that of the feature model. When one of the models is solved, the corresponding evaluator is used so that the nodes which are common to both models are evaluated according to the definition of that particular model.

[0010]   In one embodiment of the invention, a reservoir or other system which has features that are relatively constant in one dimension (e.g., vertically) is modeled in three dimensions by creating a two-dimensional finite element model for each of the different features of the system and extruding this model in the third dimension. The two-dimensional model may be defined by generating a first model and then carving out a portion of this model to accommodate a second model. The second model corresponds to a feature within the system of the first model. The first model is adapted to the boundaries of the carve-out so that each of the two models extends to the boundary between them. A plurality of nodes are common to both of the models. These common nodes may have two different values for a given property, each of which is associated with one of the models. The elements of the combined models are then extruded and subdivided into three-dimensional simplex elements. An evaluator is

associated with each of the resulting three-dimensional finite element models. When a solution for each of these models is generated, the corresponding evaluator controls the value which is associated with each of the common nodes (so that the values associated with the corresponding model are used).

[0011]   In another embodiment, a software application is configured to implement the methods described above. The software application comprises instructions which are configured to cause a computer to perform the described methods. These instructions may be stored on any type of computer readable medium. These media may include, without limitation, CD-ROMs, floppy disks, magnetic tapes, solid-state memories and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]   Other objects and advantages of the invention may become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

[0013]   FIGURE 1 is a diagram illustrating the simplices in two and three dimensions.

[0014]   FIGURE 2 is a diagram illustrating the boundaries between several features within a reservoir.

[0015]   FIGURE 3 is a diagram illustrating a two-
dimensional finite element mesh corresponding to a
portion of an oil reservoir.

[0016]   FIGURE 4 is a an expanded view of the two-
dimensional finite element mesh illustrated in FIGURE
3.

[0017]   FIGURE 5 is a flow diagram illustrating a method
according to one embodiment of the invention.

[0018]   FIGURE 6 is a diagram illustrating a three-
dimensional finite element mesh generated by
extruding the two-dimensional mesh of FIGURE 4.

[0019]   FIGURE 7 is a diagram illustrating the manner in
which a two-dimensional mesh is extruded to form a
three-dimensional mesh.

[0020]   FIGURE 8 is a diagram illustrating the manner in
which a two-dimensional simplex is adapted to form
new simplices which lie on either side of an
intersecting boundary.

[0021]   While the invention is subject to various
modifications and alternative forms, specific
embodiments thereof are shown by way of example in
the drawings and the accompanying detailed
description. It should be understood, however, that
the drawings and detailed description are not
intended to limit the invention to the particular
embodiment which is described. This disclosure is
instead intended to cover all modifications,

equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0022]   A preferred embodiment of the invention is described below. It should be noted that this and any other embodiments described below are exemplary and are intended to be illustrative of the invention rather than limiting.

[0023]   Generally speaking, the present invention comprises a method for simulating systems using a finite element modeling, as well as computer applications which embody the method and computers which are configured to perform the method. The method involves the definition of multiple, distinct finite element models which represent corresponding regions within the modeled system. Each of these finite only models comprises a set of nodes at which values are defined for various properties. For nodes which lie on boundaries between models, there are a plurality of values corresponding to a given property, wherein each of the values corresponds to a different one of the models. Each of the models is solved separately, using the values for each property which correspond to that model.

[0024]   As indicated above, the present invention may be useful in the simulation of oil reservoirs which have features that cause certain properties to vary

rapidly as a function of position within the reservoir. These features may include distinct geological strata, fractures, completion zones, damage zones, or any other feature which may cause strong heterogeneities within the reservoir. It should be noted that, while the embodiments of the invention described herein are primarily directed to the modeling of geological structures such as oil reservoirs, they may also be applied to the modeling of other systems.

[0025]   The details of a preferred embodiment will be set forth below. It may be helpful, however, to first define a few terms.

[0026]   A node is a point in space. In finite element modeling, nodes form the vertices of the elements which are modeled. The nodes also form part of a mesh of nodes and edges which define the boundaries between elements in the modeled space.

[0027]   An edge is a line between two nodes which form vertices of an element. The edges form part of the mesh which defines the boundaries between elements in the modeled space.

[0028]   A simplex is a spatial configuration of n dimensions determined by n + 1 points in a space of dimension equal to or greater than n. In other words, a—simplex is a geometric spatial element having the minimum number of boundary points necessary to enclose a space in a given number of

dimensions.   For example, in two dimensions, a simplex comprises a triangle, together with the interior area bounded by the triangle (see FIGURE 1.) Two points are insufficient to form a simplex in two-dimensional space because no area is bounded by the points (and the lines which interconnect them.) While four points may be sufficient to bound a two-dimensional area, they do not comprise the minimum number of boundary points by which the two-dimensional area can be bounded.   In three dimensions, a simplex comprises a tetrahedron, which is bounded by four vertices (see FIGURE 1.)   In four dimensions, a simplex comprises a hypertetrahedron (sometimes referred to as a hypertet) having five vertices.

[0029]   A mesh is a collection of elements that fill a space.   These elements are representative of a system which resides in that space.   Because each element can be defined by a plurality of nodes and/or the edges between those nodes, a mesh may alternatively be considered a collection of nodes and/or the edges between them.   At various points in this disclosure, "mesh" will be used to alternately refer to collections of elements or nodes/edges, depending upon the context in which the term is used.   The mesh may also be referred to herein as a finite element model or simply a model.

[0030]   Referring to FIGURE 2, a diagram illustrating the boundaries between several features within a reservoir are shown.   The figure is a sectional view

of an oil reservoir which is being modeled. Figure 2

depicts a first layer 11 which comprises a first

material (e.g., shale) which has a corresponding set

of properties. A second layer 12 is also shown.

Layer 12 comprises a second material (e.g., chalk)

which has a corresponding set of properties.

Generally speaking, the same properties (e.g.,

permeability or porosity) will be identified for both

layers for the purposes of modeling the reservoir.

The values for these properties in each of the

layers, however, may differ substantially. For

example, the permeability of one layer might be high

while the permeability of the other is low. FIGURE 2

also depicts a fracture 13 which extends through both

layer 11 and layer 12. The fracture can also be

characterized by corresponding values for each of the

identified properties. For instance, although it is

not normally used as an identifying characteristic of

a fracture (i.e., empty space,) a permeability value

(which will obviously be very high) can be assigned

to the fracture.

[0031]   When a finite element model for the reservoir

depicted in FIGURE 2 is constructed, it may comprise

three sub-models: one corresponding to layer 11; one

corresponding to layer 12; and one corresponding to

fracture 13. Each sub-model will include nodes which

lie on the boundaries between it and the other sub-

models. Generally speaking, each node which is on

one of these boundaries will be common to all of the

sub-models which share that boundary (although this

is not always the case.) Because nodes which are common to more than one sub-model will need to have different values for particular properties, depending upon the sub-model which is being evaluated, a mechanism must be provided to ensure that the proper values are used.

[0032]   In a preferred embodiment, an evaluator is associated with each of the sub-models. The evaluator controls the values of the parameters for each of the nodes on the boundaries between models. In this way, it defines parameters for each node according to the sub-model which is being solved. As a solution for a particular sub-model is computed, the evaluator corresponding to the sub-model is applied to the common nodes so that the parameters corresponding to that sub-model are used for the common nodes. Thus, a single node which lies on a boundary between two sub-models is seen as having a first set of parameters from a first one of the sub-models, but is seen as having a second set of parameters from a second one of the sub-models.

[0033]   In the present method, sub-models can be created for selected structures within a reservoir (e.g., geological strata, fractures, etc.) Using these sub-models, unique values or functions can be employed to simulate property variations within each structure. Because the sub-models are distinct, boundaries between elements with sharply contrasting properties can be accurately represented.

[0034]   Referring to FIGURES 3 and 4, a two-dimensional finite element mesh corresponding to a portion of an oil reservoir is shown to illustrate the use of distinctive sub-models to represent different regions within the reservoir. FIGURE 3 is a larger view of the mesh, while FIGURE 4 is a close-up view of the same mesh. The extent of the mesh shown in FIGURE 4 is indicated by dotted line 23 in FIGURE 3.

[0035]   The mesh shown in FIGURE 3 comprises two sub-models representing distinct features within the reservoir. The first model 21 corresponds to a partial completion area and a fracture. The second model corresponds to a separate, relatively homogeneous structure which adjoins the completion area and fracture. ("Homogeneous" is used here to refer to properties which change relatively slowly, rather than simply being constant.) Model 21 is stippled to more clearly delineate its extent.

[0036]   The elements of the mesh in FIGURES 3 and 4 are bounded by the lines which represent the edges of the elements. Each of the edges extends between two corresponding nodes of the mesh. The two-dimensional mesh can be extruded into a third dimension to form a three-dimensional finite element mesh, as will be explained in more detail below.

[0037]   Because the elements of model 22 represent a relatively homogeneous region, they can be stimulated with relative ease by a corresponding property value (or mathematical function.) The elements of model 21

are also sufficiently homogeneous within the model that the properties of the nodes in the model can be modeled by assigned values or mathematical functions. Because they are modeled by separate values and/or functions, the properties of adjacent elements in the two models (one from each model) can have sharp changes or discontinuities at the boundary between the elements.

[0038]   Referring to FIGURE 4, it can be easily seen that some of the nodes which define elements of model 21 are also used to define elements of model 22. For example, nodes 26, 27 and 28 lie on the boundary between the two models and are used to define elements of each of the models. Consequently, these nodes may have to take on different values for a given property, depending upon whether they are being evaluated with respect to one model or the other. This is achieved in the preferred embodiment by associating a unique evaluator with each of the models. When a solution is generated for a particular model, the evaluator associated with that model is used to determine the appropriate value for each of the boundary nodes.

[0039]   It should be noted that there may be nodes which lie on the boundary between two models, but which are not common to both models. Because these nodes define elements in only one of the models, they have only one value/function for each property, so there is no need to identify the model for which the node is being used to compute a solution.

[0040]   Referring to FIGURE 5, a flow diagram
illustrating a method according to one embodiment of
the invention is shown. While this figure will be
described with reference to an oil reservoir as the
modeled system, the same methodology can be applied
to other systems as well. In this method, an initial
finite element mesh corresponding to the overall
reservoir is generated and then separate finite
element meshes corresponding to features within the
reservoir are inserted into the first mesh. This
first mesh is adapted to accommodate the new,
secondary meshes. In other words, the regions
occupied by the secondary meshes are carved out of
the first mesh so that no two meshes occupy the same
space.

[0041]   The initial finite element mesh, as adapted to
accommodate the other meshes, will serve as a model
for one of the regions of the reservoir. (Although
this region may be smaller than the other regions in
some cases, it will typically represent the bulk of
the reservoir.) This mesh can be generated by any
suitable means known to persons of skill in the art
of finite element modeling. An unstructured mesh of
simplex elements is preferred. After the first mesh
is generated, a feature is defined and then a
secondary region is carved out of the first mesh to
accommodate the secondary region. A mesh is
generated within the boundaries defined for the
feature. The mesh may be constructed before the
secondary region is carved out of the first mesh, or

it may be generated afterwards. In either case, two separate finite element models corresponding to the different regions of the modeled system are created. These models are immediately adjacent to each other (i.e., there is a common boundary between them.) This process may be repeated for additional features in the modeled system (and additional secondary regions within the first finite element mesh).

[0042]   In the preferred embodiment, this process is actually carried out in two dimensions to generate a mesh which is then extruded into three dimensions. For example, if it is assumed that the completion zone and fracture represented by model 21 in FIGURE 4 represent features in a horizontal plane, the two-dimensional mesh shown in the figure can be extruded vertically to generate a three-dimensional mesh. This is illustrated in FIGURE 6.

[0043]   FIGURE 6 shows the two-dimensional mesh of FIGURE 4 from an oblique angle. This two-dimensional mesh is extruded vertically (as indicated by the dotted lines) to form a plurality of three-dimensional prisms. In a preferred embodiment, these prisms are subdivided into three-dimensional simplices (tetrahedra.) The generation of a three-dimensional mesh in this manner may reduce the computational requirements of mesh generation by confining the adaptation process (the dividing of the initial mesh into two separate meshes) to two dimensions and then extruding the refined two-dimensional mesh. This eliminates what is effectively the separate

refinement of the same two-dimensional mesh several times at different points in the third dimension.

[0044]   While the extrusion process will not be described in detail in this disclosure, FIGURE 7 is presented herein to illustrate the manner in which the extrusion from two dimensions to three dimensions is accomplished. FIGURE 7 shows a single, two-dimensional simplex (a triangle) which is extruded to form a three-dimensional prism. This prism is then subdivided into three three-dimensional simplices (tetrahedra). It should be noted that this same procedure can be used to extrude a three-dimensional mesh in a fourth dimension (e.g., time.)

[0045]   In one embodiment, the boundaries of the different regions are determined before any of the meshes are generated. When the different regions are defined, a mesh is constructed within each region. Each mesh is constructed so that it extends to the boundaries which are shared by the meshes (as well as the outer extent of the entire modeled system.) The generation of the mesh may be performed in any suitable manner. Any desired number of regions can be defined and corresponding meshes can be generated within these regions.

[0046]   In another embodiment, the first mesh is generated so that it fills the entire space of the modeled system. A boundary is then defined to separate the regions of the system. Since this boundary may cut existing elements into two pieces,

the mesh in each region is adapted to form valid
simplices in place of the intersected elements. This
results in two meshes corresponding to the two
regions of the system.

[0047]   Although the adaptation process will not be
described in great detail, FIGURE 8 is presented to
provide an illustration of the process. FIGURE 8
comprises three views of a two-dimensional simplex (a
triangle) which is adapted to form simplices on each
side of a boundary. In the first figure, the simplex
is shown intersected by a boundary curve. The edges
of the simplex are intersected at two points. A new
node is created at each of the intersections. A new
edge is then defined between one of the new nodes and
the opposite vertex of the simplex, forming two new
simplices. A new edge is then defined between the
remaining new node and the opposite vertex of the new
simplex. This procedure results in three new
simplices -- one above the boundary, and two below
it.

[0048]   Essentially the same procedure can be performed
in the case of three-dimensional simplices. The
resulting simplices will lie essentially on one side
or the other of the boundary. (Because the boundary
may be curved, the simplices, which have flat
surfaces, may not lie exactly on the boundary.)
Since the adaptation process produces simplices which
are almost entirely on one side of the boundary, they
can each be defined as part of the first region or

the second region, hence part of the first finite element model or the second.

[0049]   It should be noted that the preceding paragraphs describing the creation of finite element models corresponding to different regions of the modeled system are applicable to n-dimensional meshes.

[0050]   Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or element of any or all the claims. As used herein, the terms "comprises," "comprising," or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

[0051]   While the present invention has been described with reference to particular embodiments, it should be understood that the embodiments are illustrative and that the scope of the invention is not limited to these embodiments. Many variations, modifications, additions and improvements to the embodiments described above are possible. Particularly, these

variations may include computers or other data
processing devices, computer readable media (such as
floppy disks, CD-ROMs, DVD-ROMs, etc.,) storage
devices, computer memories and the like which contain
software, firmware or other programming embodying the
foregoing methods. It is contemplated that these
variations, modifications, additions and improvements
fall within the scope of the invention as detailed
within the following claims.